Electronic Supplementary Information

Size-dependent magnetic and inductive heating properties of Fe_3O_4 nanoparticles: Scaling laws across the superparamagnetic size

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a. Percentage yield calculation

The percentage yield can calculate using the formula:

$$Percent\ yield = \left(\frac{Actual\ yield}{Theoritical\ yield}\right) \times 100 = 84\ \%$$

Where, the theoretical yield = 7.7 g (100 mmol (35 g) of $Fe(acac)_3 \rightarrow$ 33.3 mmol (7.7 g) of Fe_3O_4) and the actual yield = 6.5 g (after subtracting the organic contribution ~ 20 %).

Table S1: Mole concentration of $Fe(acac)_3$, OAm and OA used for the synthesis of Fe_3O_4 nanoparticles (3-32 nm). Average nanoparticle size determined from XRD and TEM analysis.

$Fe(acac)_3$ (mM)	OAm (mM)	OA (mM)	$Fe(acac)_3$:OAm :OA mole ratios	MNP size from XRD (nm)	MNP size from TEM (nm)	Lattice constant (Å)
20	180	0	1:9:0	3.5 ± 0.2	3.0 ± 0.5 nm	8.37
20	140	0	1:7:0	4.3 ± 0.5	4.1 ± 0.7 nm	8.38
20	100	0	1:5:0	6.1 ± 0.4	6.0 ± 0.8 nm	8.38
20	60	0	1:3:0	9.6 ± 0.5	8.8 ± 1.1 nm	8.38
20	60	10	2:6:1	12.9 ± 0.7	12.0 ± 1.5 nm	8.38
20	60	20	2:6:2	16.4 ± 1	15.8 ± 1.6 nm	8.39
20	60	30	2:6:3	20 ± 0.2	19.9 ± 1.8 nm	8.39
20	60	50	2:6:5	36 ± 5 (mixed shapes)		
20	60	70	2:6:7	viscous brown color product		
20	60	30	2:6:3	24. 6 ± 1.8	24.1 ± 1.6	8.39
30	60	30	3:6:3	30 ± 2	27.6 ± 1.9	8.39
40	60	30	4:6:3	31± 2.5	32.4 ± 2.5	8.39

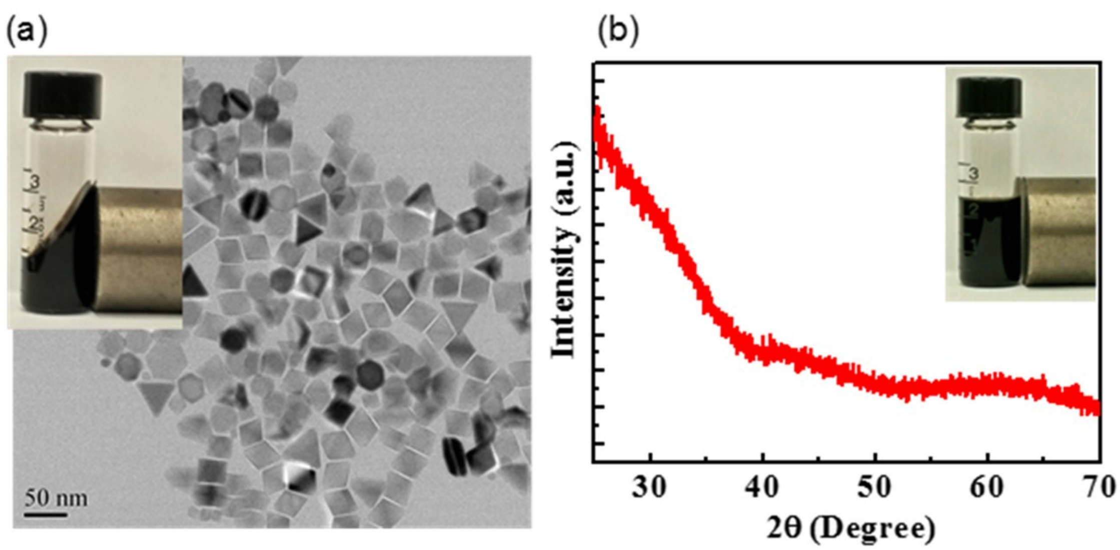

Fig. S1. (a) TEM images of Fe_3O_4 nanoparticles synthesized using Fe-precursor to OAm and OA mole ratio (Fe-precursor: OAm: OA) as 2:6:5. Inset shows that the nanoparticles are well dispersed in the toluene and attracted by a magnet. (b) XRD pattern of the viscous red-brown product obtained when the mole ratio of OAm to OA is increased to 6:7. Inset shows that the toluene dispersion of the final product is non-magnetic.

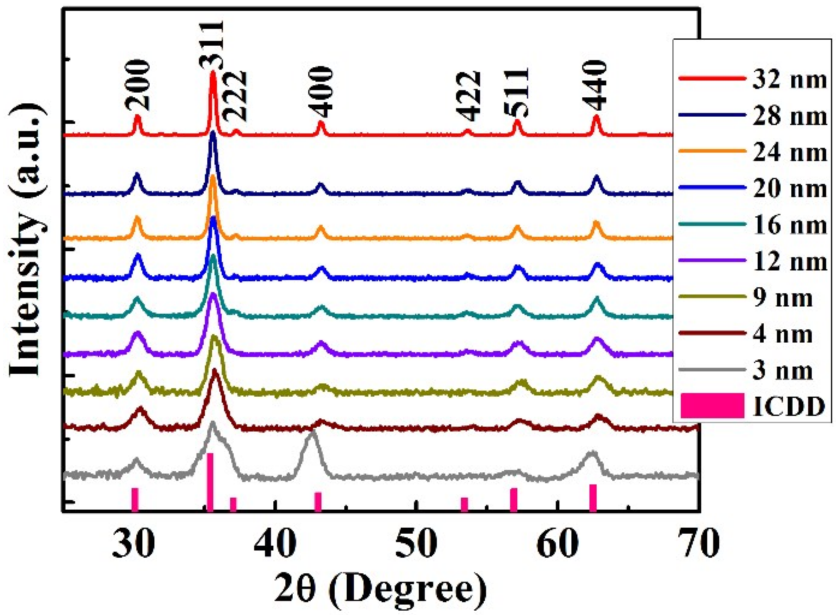

Fig. S2. XRD patterns of Fe_3O_4 of different sizes. The XRD patterns for all the samples are matched with standard Fe_3O_4 spinel phase (ICDD card No. 01-079-0418).

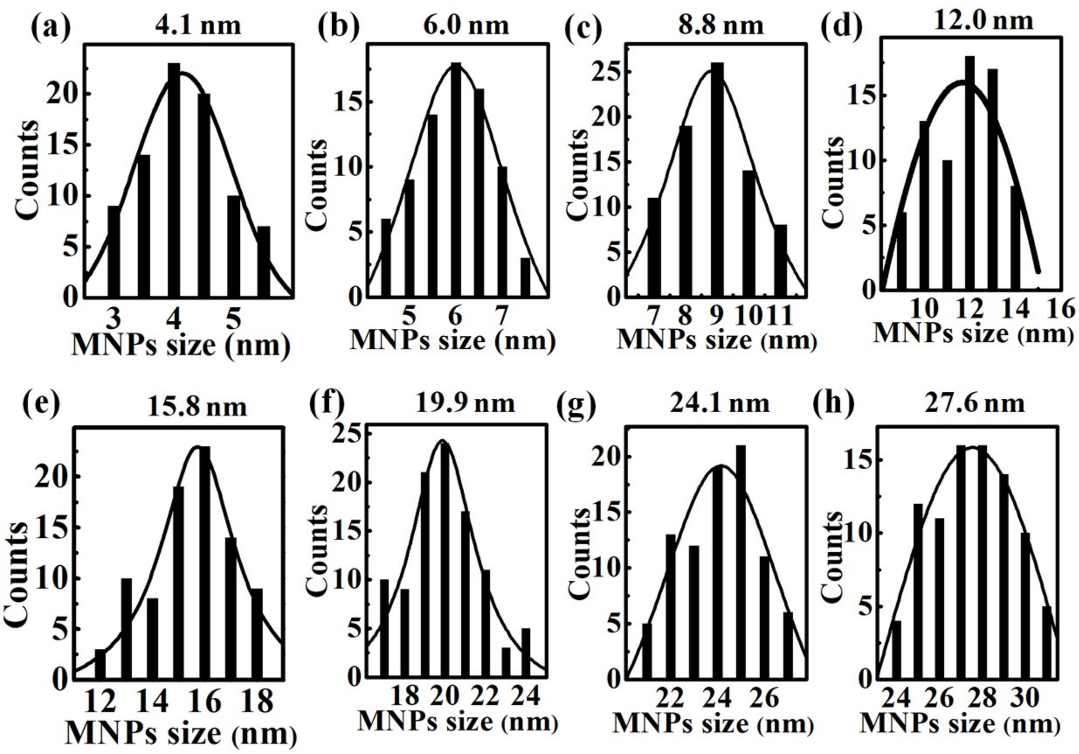

Fig. S3: Particle size distribution histograms of OA/OAm coated- Fe_3O_4 nanoparticles synthesized with manipulation of Fe-precursor to OAm and OA mole ratio (Fe-precursor: OAm: OA) as (a) 1:7:0, (b) 1:5:0, (c) 1:3:0 (d) 2:6:1, (e) 2:6:2, (f) 2:6:3, (g) 2:6:3 and (h) 3 :6:3. In 24-28 nm sized MNP case, the OAm was injected into the reaction medium at 200 °C.

Table S2. Mössbauer parameters: hyperfine field (H_{hf}), quadrupole splitting (Q_S), and isomer shift (I_S) for Fe_3O_4 nanoparticles

MNPs size	iron sites	hyperfine field (H_{hf}), kOe	quadrupole splitting (Q_S), mm/s	isomer shift (I_S), mm/s
4 nm	sextet B	489.10	0.00	0.54
	sextet A	458.16	0.01	0.16
	singlet C			0.96
16 nm	sextet B	456.96	0.00	0.54
	sextet A	488.75	0.00	0.18
28 nm	sextet B	456.77	0.00	0.54
	sextet A	488.50	0.00	0.18

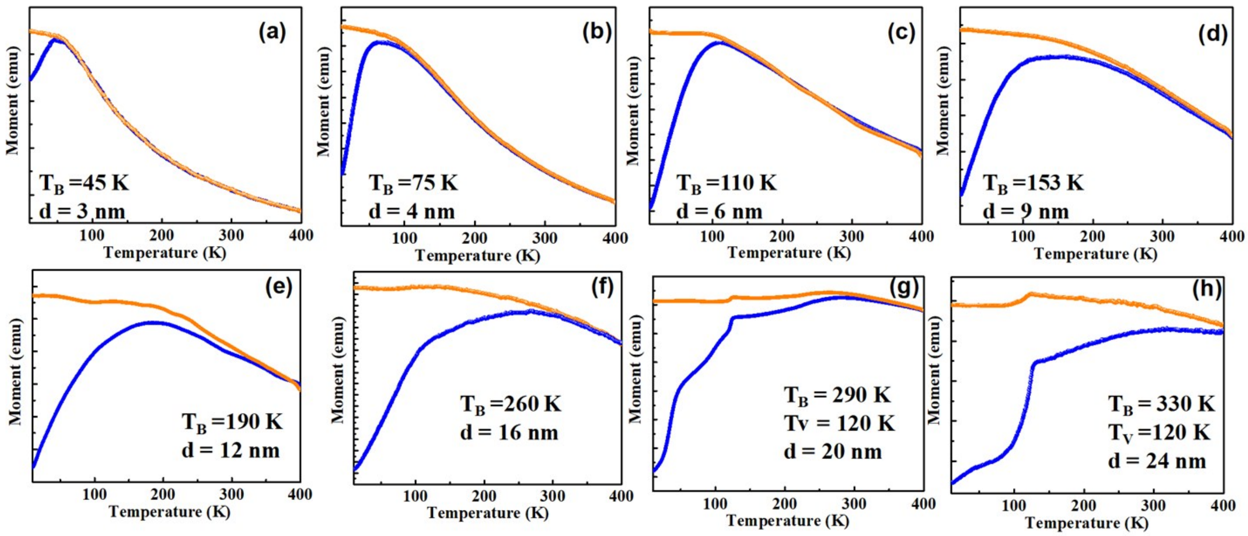

Fig. S4. Temperature dependence of low field (50 Oe) ZFC (blue)–FC (orange) magnetization of (a) 3, (b) 4, (c) 6, (d) 9, (e) 12, (f) 16, (g) 20 nm and (f) 24 nm Fe_3O_4 nanoparticles. The blocking temperature increases with the increase of nanoparticles size.

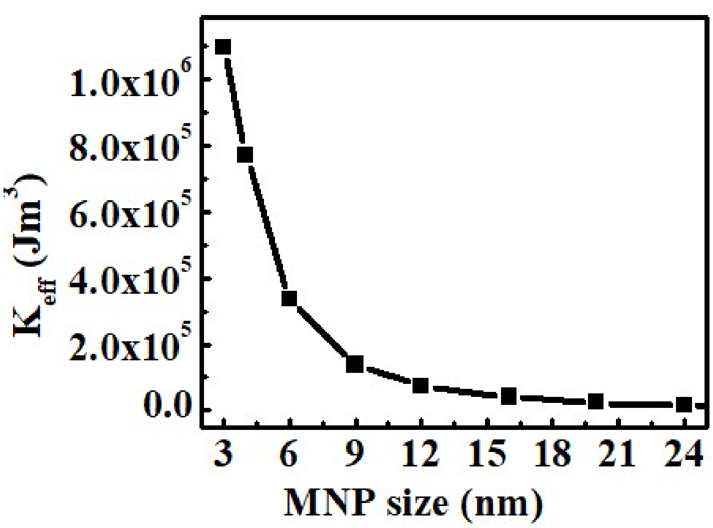

Fig. S5: The effective anisotropy constant (K_{eff}) variation with the Fe_3O_4 nanoparticles size.

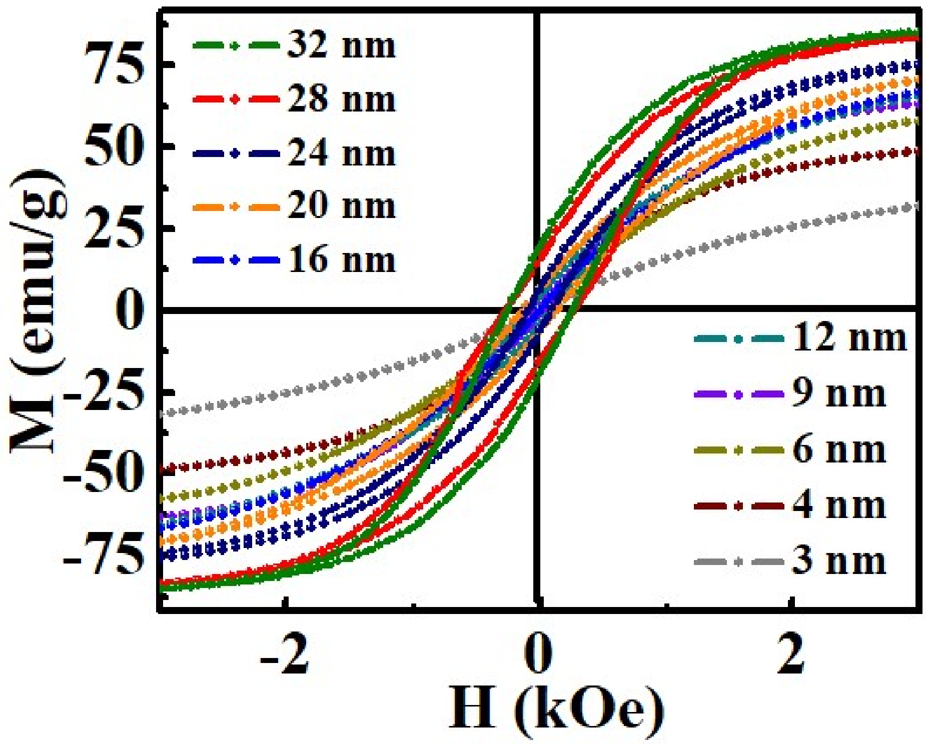

Fig. S6: Room temperature field-dependent magnetization curves of different sized Fe_3O_4 nanoparticles.

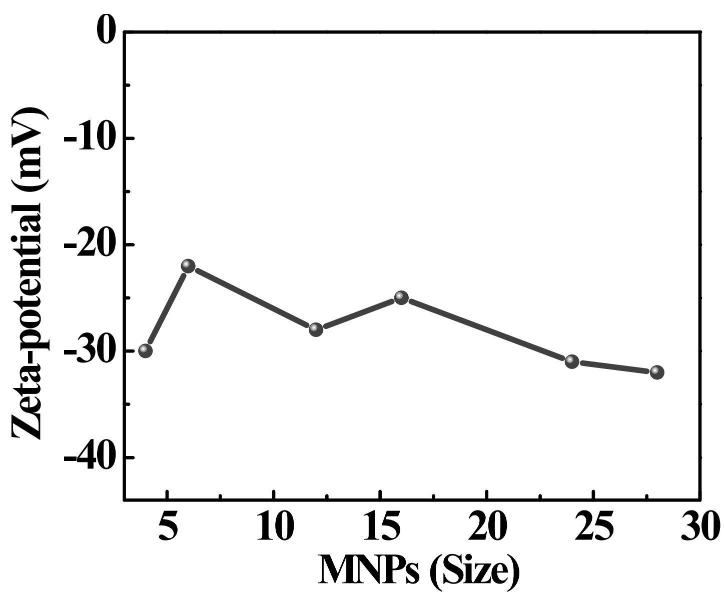

Fig. S7: Zeta potential value of the aqueous dispersion 3-28 nm citric acid coated Fe_3O_4 nanoparticles.

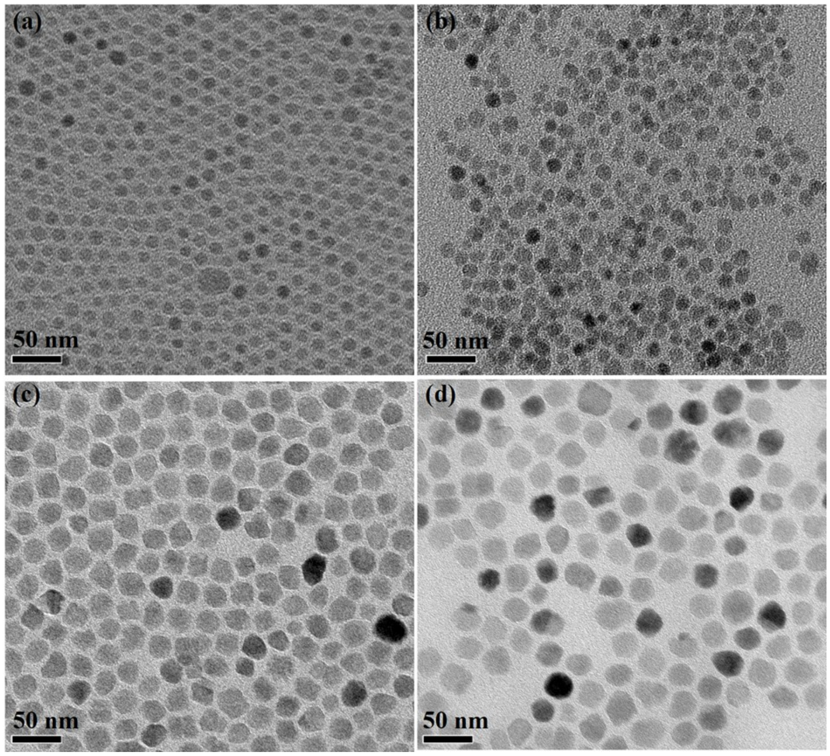

Fig. S8: TEM micrographs of Fe_3O_4 nanoparticles of average size 9 nm (a and b) and 28 nm (c and d) as prepared (dispersible in hexane) and citric acid functionalized (dispersible in water).

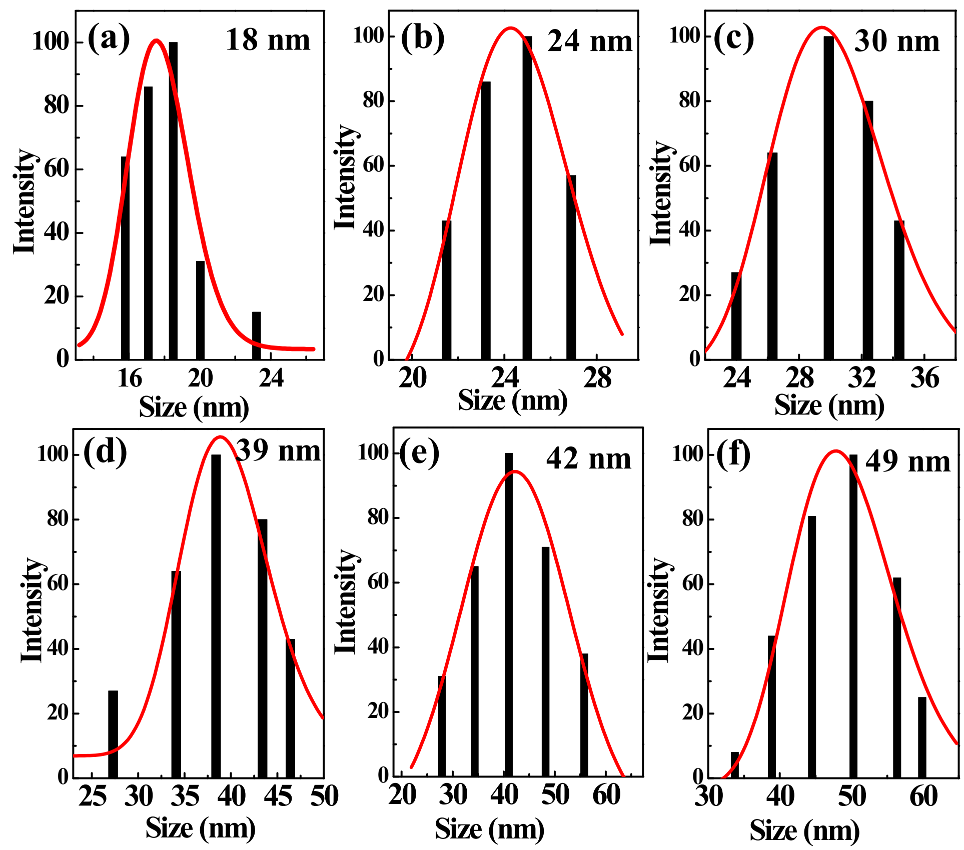

Fig. S9: Hydrodynamic diameter of different citric acid functionalized sized Fe_3O4 nanoparticles of average TEM size: (a) 4 nm, (b) 9 nm, (c) 16 nm, (d) 20 nm, (e) 24 nm and (f) 28 nm.

Table S3: The average TEM size, the average hydrodynamic size, saturation magnetization values of as prepared and citric acid functionalized Fe_3O_4 nanoparticles.

Sample name	As synthesized MNPs		Citric acid MNPs				Six months old MNPs dispersion
	Average size (TEM)	M_S (emu/g)	Average hydrodynamic diameter (nm)	Polydispersity	M_S (emu/g)	SAR value (W/g)	Average hydrodynamic diameter (nm)
3	3.0 ± 0.5 nm	48			42	27	
4	4.1 ± 0.7 nm	56	18 ± 2.6 nm	0.02	51	43	19 ± 3.2 nm
6	6.0 ± 0.8 nm	65			64	75	
9	8.8 ± 1.1 nm	74	24 ± 2.9 nm	0.08	70	132	22 ± 3.0 nm
12	12.0 ± 1.5 nm	78			75	189	
16	15.8 ± 1.6 nm	83	30 ± 3.1 nm	0.11	79	298	32 ± 3.5 nm
20	19.9 ± 1.8 nm	84	39 ± 4.5 nm	0.18	79	480	40 ± 3.8 nm
24	24.1 ± 1.6 nm	87	42 ± 3.0 nm	0.16	80	670	44 ± 3.6 nm
28	27.6 ± 1.9 nm	88	49 ± 3.0 nm	0.12	82	801	51 ± 4.2 nm
32	32.4 ± 2.5 nm	88			83	520	

Table S4: Comparison of the hyperthermia heating performance of 28 nm Fe_3O_4 nanoparticles with the reported results.

Iron oxide nanoparticle	**Coating**	**Magnetic properties**	**Hydrodynamic**	**ACMF amplitude/**	**SAR**	**Ref.**

size	material	at room temperature	size	Frequency	W/g	
28 nm Nanoparticles	Citric acid	*Ms*= 82 emu/g *Hc* = 270 Oe	49 ± 3.0 nm	625 Oe 265 kHz	801 W/g	This work
19± 3 nm Nano-cubes	Polyethylene glycol	*Ms*=80 emu/g *Hc* = 0		29 kA/m 520 kHz	2452 W/g of Fe	[1]
13.7 nm Nanoparticles	3-aminopropyl)triethoxysilane	*Ms*= 70 emu/g *Hc* = 0	68 nm	7.5 kA/m 522.7 kHz.	55 W/g	[2]
47 nm Nano-ctopods	Tetramethylammonium hydroxide	*Ms*= 81.7 emu/g *Hc* = 103 Oe		800 Oe 310 kHz	415 W/g	[3]
22.5 nm nanoparticles	Dimercaptosuccinic acid	*Ms*= 65 emu/g *Hc* = 10 Oe	48 nm	140 Oe 110 kHz	322 W/g	[4]
40.4 nm Nanoparticles	amphiphilic copolymer DSPE-PEG2000	*Ms*= 116.1 emu/g Fe	52.4 nm	13.3 kA/m 325 kH	~ 2500 W/g of Fe	[5]
43 nm Nano-octahedral	Cetrimonium bromide	*Ms*= 85 emu/g *Hc* =37 Oe		800 Oe 358 kHz	2483 W/g of Fe	[6]

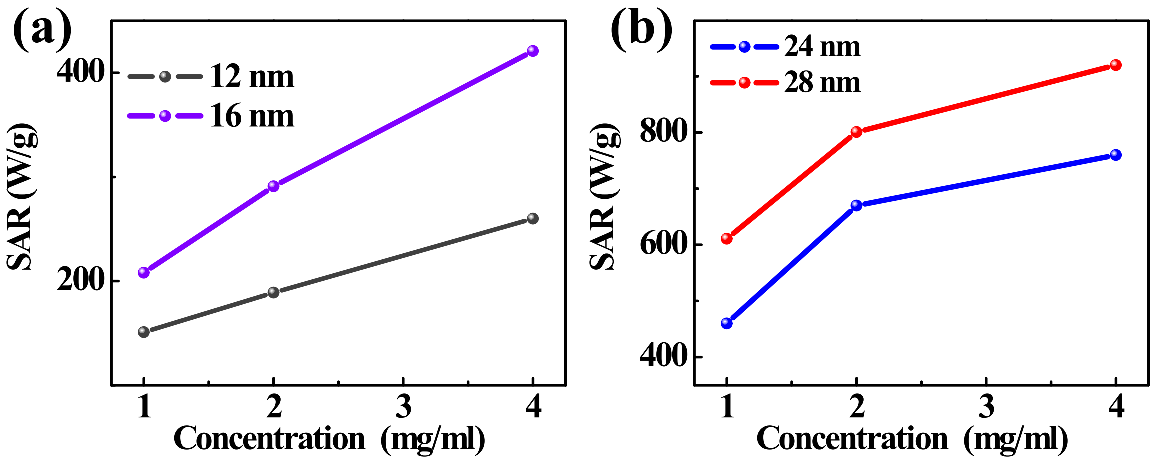

Fig. S10: The SAR vs Fe_3O_4 concentration for: (a) 12 and 16 nm and (b) 24 and 28 nm MNPs.

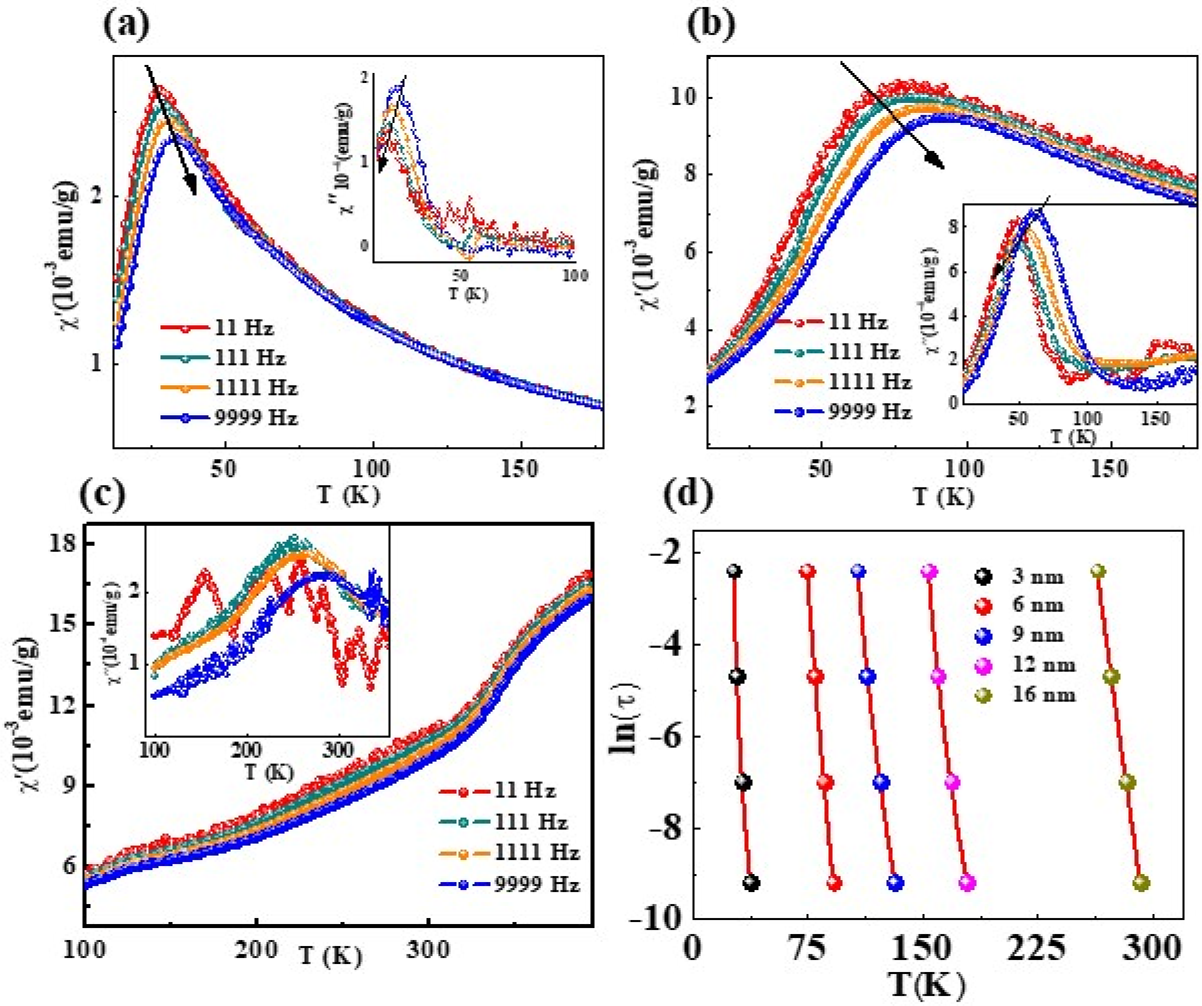

Fig. S11. In-phase ($\chi'(T, f)$) and out-of-phase ($\chi''(T, f)$) (inset) components of the AC susceptibility for (a) 3 nm, (b) 6 nm and (c) 20 nm Fe_3O_4 nanoparticles. (d) The frequency dependence of blocking temperature (T_B) of $\chi'(T, f)$ is fitted with Vogel–Fulcher law.

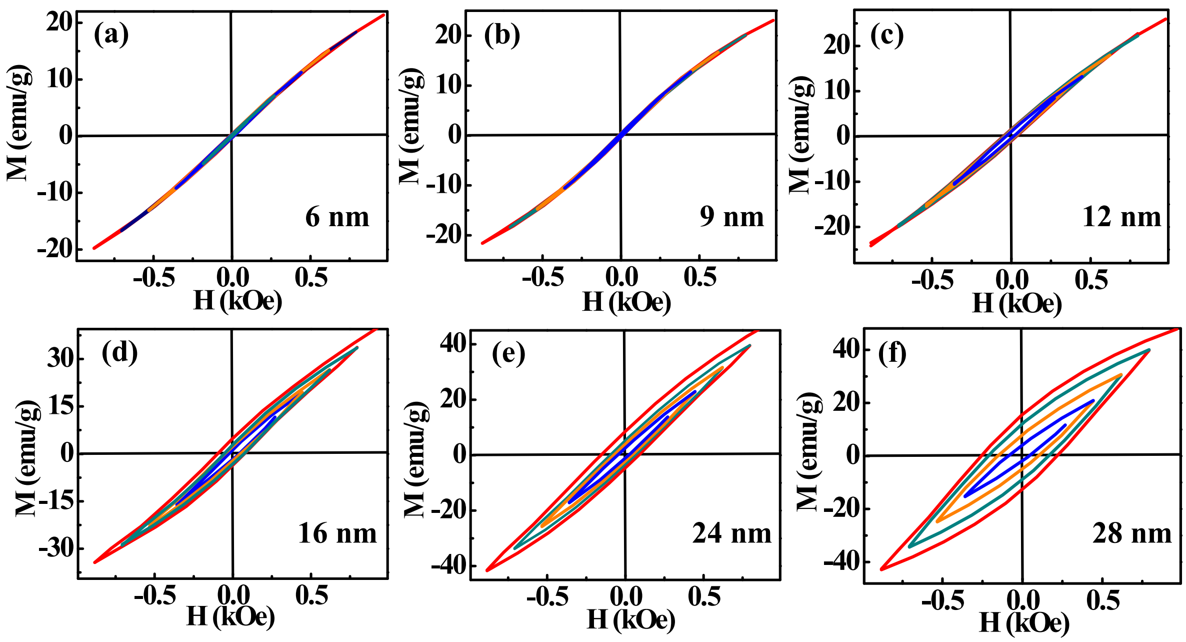

Fig. S12: Room temperature minor M−H loop at maximum magnetic field of 200 (blue), 400 (orange), 600 (green) and 800 Oe (red): (a) 6, (b) 9, (c) 12, (d) 16, (e) 24 and (f) 28 nm Fe_3O_4 nanoparticles.